

# CHARMING PENGUINS STRIKE BACK

M. Ciuchini<sup>1</sup>, E. Franco<sup>2</sup>, G. Martinelli<sup>2</sup>, M. Pierini<sup>2</sup>, L. Silvestrini<sup>2</sup>

<sup>1</sup> Dip. di Fisica, Univ. di Roma Tre and INFN, Sezione di Roma Tre,  
Via della Vasca Navale 84, I-00146 Roma, Italy

<sup>2</sup> Dip. di Fisica, Univ. “La Sapienza” and INFN,  
Sezione di Roma, P.le A. Moro, I-00185 Rome, Italy.

## Abstract

By using the recent experimental measurements of  $B \rightarrow \pi\pi$  and  $B \rightarrow K\pi$  branching ratios, we find that factorization is unable to reproduce the observed  $BR$ s even taking into account the uncertainties of the input parameters. Charming and GIM penguins allow to reconcile the theoretical predictions with the data. Because of these large effects, we conclude, however, that it is not possible, with the present theoretical and experimental accuracy, to determine the CP violation angle  $\gamma$  from these decays. Contrary to factorization, we predict large asymmetries for several of the particle–antiparticle  $BR$ s, in particular  $BR(B^+ \rightarrow K^+\pi^0)$ ,  $BR(B_d \rightarrow K^+\pi^-)$  and  $BR(B_d \rightarrow \pi^+\pi^-)$ . This opens new perspectives for the study of CP violation in  $B$  systems.

# 1 Introduction

The theoretical understanding of non-leptonic two body  $B$  decays is a fundamental step for testing flavour physics and CP violation in the Standard Model and for detecting signals of new physics [1]–[5]. The increasing accuracy of the experimental measurements at the  $B$  factories [6, 7] calls for a significant improvement of the theoretical predictions. In this respect, important progress has been recently achieved by systematic studies of factorization made by two independent groups [8, 9]. These studies, while confirming the physical idea [10] that factorization holds for hadrons containing heavy quarks,  $m_Q \gg \Lambda_{QCD}$ , give the explicit formulae necessary to compute quantitatively the relevant amplitudes at the leading order of the  $\Lambda_{QCD}/m_Q$  expansion. They also examine some of the contributions entering at higher order in  $\Lambda_{QCD}/m_Q$ . The question which naturally arises is whether in practice the power-suppressed corrections, for which quantitative estimates are missing to date, may be phenomenologically important for  $B$  decays. This problem was previously addressed in refs. [11, 12, 13]. In particular, the main conclusion of refs. [11] was that *non-perturbative* penguin contractions of the leading operators of the effective weak Hamiltonian,  $Q_1$  and  $Q_2$ , although formally of  $\mathcal{O}(\Lambda_{QCD}/m_Q)$ , may be important in cases where the factorized amplitudes are either colour or Cabibbo suppressed. The most dramatic effect of these non-factorizable penguin contractions manifested itself in the very large enhancement of the  $B \rightarrow K\pi$  branching ratios, as was also emerging from the first measurements by the CLEO Collaboration [14]. In this case, the effect was triggered by Cabibbo-enhanced penguin contractions of the operators  $Q_1^c$  and  $Q_2^c$ , usually referred to as *charming penguins*. Since the original publications, about three years ago, several other decay channels have been measured [15, 16, 17] and the precision of the measurements is constantly improving. With respect to previous analyses, it is now possible to attempt a more quantitative study of charming penguin effects and of the corrections expected to the factorized predictions. We now present the main conclusions of our new analysis.

## Factorization with $|V_{ub}|$ and $\gamma$ from other determinations

Using the available experimental information on  $|V_{ub}|$  and on the CP angle  $\gamma$  provided by the unitarity triangle analysis (UTA) [18], the branching ratios predicted with the factorized amplitudes, including the  $\mathcal{O}(\alpha_s)$  corrections computed according to ref. [9], fail to reproduce the experimental  $B \rightarrow K\pi$  branching ratios that are systematically larger than the theoretical predictions. In addition,  $BR(B_d \rightarrow \pi^+\pi^-)$ , which depends on the semileptonic form factor  $f_\pi(0)$ , is about a factor of 2 larger than its experimental value<sup>1</sup>. We note that the value of  $BR(B_d \rightarrow \pi^+\pi^-)$  within factorization is essentially fixed by the measured  $BR(B^+ \rightarrow \pi^+\pi^0)$  rate. Thus, contrary to the statement of ref. [9], the predicted value of  $BR(B_d \rightarrow \pi^+\pi^-)$  is independent of the theoretical assumptions on the value of  $f_\pi(0)$ . This holds essentially true also for the  $B \rightarrow K\pi$  BRs since the value

---

<sup>1</sup>Unless explicitly stated the BRs always refer to the average of particles and antiparticles, e.g.  $BR(B_d \rightarrow K^0\pi^0) \equiv 1/2(BR(\bar{B}_d^0 \rightarrow \bar{K}^0\pi^0) + BR(B_d^0 \rightarrow K^0\pi^0))$ .

of the “semileptonic” form factor at zero momentum transfer  $f_K(0)$  is correlated to  $f_\pi(0)$  by the approximate  $SU(3)$  symmetry.

### Factorization fitting $\gamma$

Even if one ignores the value of  $\gamma$  from UTA, which is only justified if there are contributions to  $\Delta F = 2$  mixing due to physics beyond the Standard Model, there are serious difficulties in reproducing the experimental results. In particular,  $BR(B_d \rightarrow K^0 \pi^0)$  and  $BR(B^+ \rightarrow K^0 \pi^+)$  are much smaller than their experimental values. Moreover, the value of  $\gamma$  extracted from a fit to the data,  $\gamma = (163 \pm 12)^\circ$ , is in total disagreement with that from the UTA,  $\gamma = (54.8 \pm 6.2)^\circ$  [18]. In addition, in order to enhance the  $B \rightarrow K\pi$  rates, the preferred values of  $f_K(0) = 0.40 \pm 0.02$  and  $f_\pi(0) = 0.34 \pm 0.01$  are incompatible with the latest theoretical estimates,  $f_\pi(0) = 0.26 \pm 0.05 \pm 0.04$ ,  $f_K(0)/f_\pi(0) = 1.21 \pm 0.09_{-0.09}^{+0.00}$  [19] and  $f_\pi(0) = 0.28 \pm 0.05$ ,  $f_K(0)/f_\pi(0) = 1.28_{-0.10}^{+0.18}$  [20], whereas  $|V_{ub}|$  must have a rather low value,  $|V_{ub}| = (2.79 \pm 0.19) \times 10^{-3}$  instead of that extracted from inclusive [21] and exclusive [22] semileptonic  $B$  decays,  $|V_{ub}| = (3.25 \pm 0.29 \pm 0.55) \times 10^{-3}$ . We conclude that, even relaxing the constraint on  $\gamma$ , it is very difficult to reconcile the predictions from factorization with the experimental and theoretical findings. For this reason any attempt to extract, within factorization, the value of  $\gamma$  from ratios of  $BR$ s, for which the discrepancies with the experiments can be accidentally hidden, is not very useful. We think that a preliminary step is to understand the missing dynamical effects.

### Factorization and charming penguins

The inclusion of charming penguin effects, which will be explained in detail in sec. 2, considerably improves the situation for the  $B \rightarrow K\pi$  channels, with values of  $|V_{ub}|$  and  $\gamma$  well compatible with other determinations. In contrast to the  $B \rightarrow K\pi$  case, charming penguins are not Cabibbo enhanced in  $B \rightarrow \pi\pi$  decays and are thus expected *a priori* to play a minor role. For this reason they should be consistently neglected, together with all other  $\Lambda_{QCD}/m_b$  corrections. This would leave the problem of a too large predicted  $BR(B_d \rightarrow \pi^+ \pi^-)$  unsolved. A natural question is then whether the inclusion of  $\Lambda_{QCD}/m_b$  effects in  $B_d \rightarrow \pi^+ \pi^-$  can improve the agreement of the predictions with the experimental data. In particular, besides the charming penguins, penguin contractions of  $Q_1^u$  and  $Q_2^u$  (GIM penguins in the notation of ref. [11]), which are Cabibbo suppressed in  $B \rightarrow K\pi$ , might play an important rôle. We show that, for numerical values of the charming and GIM penguin amplitudes of the expected size,  $\Lambda_{QCD}/m_b \sim 0.1$ – $0.2$ , we can easily reproduce the experimental data for both  $B \rightarrow K\pi$  and  $B \rightarrow \pi\pi$  decays while respecting the constraints from the UTA. The sensitivity of  $B \rightarrow \pi^+ \pi^-$  to  $\Lambda/m_b$  effects casts serious doubts on the possibility of extracting  $\sin 2\alpha$  from the coefficient of the  $\sin \Delta m_{B_d} t$  term obtained from CP asymmetry measurements. On the other hand, we find that the value of the rate asymmetry,

$$\mathcal{A}(B_d \rightarrow \pi^+ \pi^-) = \frac{BR(\bar{B}_d^0 \rightarrow \pi^+ \pi^-) - BR(B_d^0 \rightarrow \pi^+ \pi^-)}{BR(\bar{B}_d^0 \rightarrow \pi^+ \pi^-) + BR(B_d^0 \rightarrow \pi^+ \pi^-)}, \quad (1)$$

could be unexpectedly large and call our experimental colleagues for separate measurements of the  $B$  and  $\bar{B}$  BRs. In particular, we find  $|\mathcal{A}(B^\pm \rightarrow K^\pm \pi^0)| = 0.18 \pm 0.06$ ,  $|\mathcal{A}(B_d \rightarrow K^\pm \pi^\mp)| = 0.17 \pm 0.06$ . We also find  $|\mathcal{A}(B_d \rightarrow \pi^+ \pi^-)| = 0.30 - 0.50$ . In the latter case, as discussed in the following, the results are subject to other effects on which we do not have control. For this reason we do not quote an error. We simply signal that there is room for a large asymmetry also in  $B_d \rightarrow \pi^+ \pi^-$  decays.

## 2 Results

In this section we describe and discuss more in detail the different cases which have been considered in our analysis.

The physical amplitudes for  $B \rightarrow K\pi$  and  $B \rightarrow \pi\pi$  are more conveniently written in terms of RG invariant parameters built using the Wick contractions of the effective Hamiltonian [23]. In the heavy quark limit, following the approach of ref. [9], it is possible to compute these RG invariant parameters using factorization. The formalism has been developed so that it is possible to include also the perturbative corrections to order  $\alpha_s$ , i.e. at the next-to-leading order in perturbation theory. We present results obtained with this formalism with the addition of the non-perturbative  $\Lambda_{QCD}/m_b$  corrections to factorization described below in this section. An alternative framework is provided by the approach of ref. [8]. This method differs in the treatment of the  $\mathcal{O}(\alpha_s)$  terms; unlike the method of ref. [9], the calculations are only valid at the leading logarithmic order and it is not clear how the independence of the final result from the renormalization scale of the operators of the effective Hamiltonian is recovered. Moreover the Sudakov suppression of the endpoint region, advocated in [8], is still rather controversial from both the theoretical and phenomenological point of view. For these reasons we prefer to postpone the analysis with the approach of ref. [8] until the theoretical situation will become clearer.

In the leading amplitudes, we have taken into account the  $SU(3)$  breaking terms by using the appropriate decay constants,  $f_K$  and  $f_\pi$ , and form factors,  $f_K(0)$  and  $f_\pi(0)$ . Strictly speaking, the form factors should be evaluated at the invariant mass of the emitted meson ( $f_K(m_\pi^2)$ ,  $f_\pi(m_K^2)$  or  $f_\pi(m_\pi^2)$ ). The difference is however of higher order in  $\Lambda_{QCD}/m_b$  and not Cabibbo or colour enhanced and can safely be neglected (it is also numerically immaterial) [24]. As for  $\Lambda_{QCD}/m_b$  corrections, we have assumed instead  $SU(3)$  symmetry and neglected Zweig-suppressed contributions. In this approximation, by  $SU(3)$  symmetry one can show that all the Cabibbo-enhanced  $\Lambda_{QCD}/m_b$  corrections to  $B \rightarrow K\pi$  decays can be reabsorbed in a single parameter  $\tilde{P}_1$ . Several corrections are contained in  $\tilde{P}_1$ : this parameter includes not only the charming penguin contributions, but also annihilation and penguin contractions of penguin operators. It does not include leading emission amplitudes of penguin operators ( $Q_3$ – $Q_6$ ) which have been explicitly evaluated using factorization. Had we included these terms, this contribution would exactly correspond to the parameter  $P_1$  of ref. [23]. The parameter  $\tilde{P}_1$  ( $P_1$ ) encodes automatically not only the effect of the annihilation diagrams considered in [25], but

all the other contributions of  $\mathcal{O}(\Lambda_{QCD}/m_b)$  with the same quantum numbers of the charming penguins. In this respect it is the most general parameterization of all the perturbative and non-perturbative contributions of the operators  $Q_5$  and  $Q_6$  ( $Q_3$  and  $Q_4$ ), including the worrying higher-twist infrared divergent contribution to annihilation discussed in ref. [26]. The parameter  $\tilde{P}_1$  is of  $\mathcal{O}(\Lambda_{QCD}/m_b)$  and has the same quantum numbers and physical effects as the original charming penguins proposed in [11], although it has a more general meaning. In some of the previous analyses, see for example [27], penguin contractions of the operator  $Q_6$ , computed by using perturbation theory and factorization, are enhanced by taking a low effective scale for  $\alpha_s$ . This procedure produces a physical effect similar to that coming from the non-perturbative charming penguins that we are using here, since they have the same quantum numbers.

If one also includes  $B \rightarrow \pi\pi$  decays we have several other parameters, for example  $P_1^{\text{GIM}}$  and  $P_3$ , in the formalism of ref. [23]. A closer look to  $P_3$  shows that this term is due either to Zweig suppressed annihilation diagrams (called CPA and DPA in ref. [11]) or to annihilation diagrams which are colour suppressed with respect to those entering  $\tilde{P}_1$ . For this reason we have put  $P_3$  to zero.  $P_1^{\text{GIM}}$  will be discussed later on.

We give now the explicit expression of the  $B_d \rightarrow K^+\pi^-$  amplitude as an illustrative example. In terms of the parameters defined in [23], this amplitude reads

$$\begin{aligned} \mathcal{A}(B_d \rightarrow K^+\pi^-) = & -V_{us}V_{ub}^* \left( E_1(s, u, u; B_d, K^+, \pi^-) - P_1^{\text{GIM}}(s, u; B_d, K^+, \pi^-) \right) \\ & + V_{ts}V_{tb}^* P_1(s, u; B_d, K^+, \pi^-). \end{aligned} \quad (2)$$

Using the approach of [9], we have

$$\begin{aligned} E_1(s, u, u; B_d, K^+, \pi^-) &= a_1^u(K\pi) \langle Q_1^u \rangle_{\text{fact}} + a_2^u(K\pi) \langle Q_2^u \rangle_{\text{fact}} + \tilde{E}_1 \\ P_1(s, u; B_d, K^+, \pi^-) &= \sum_{i=3}^6 a_i^c(K\pi) \langle Q_i \rangle_{\text{fact}} + \tilde{P}_1 \\ P_1^{\text{GIM}}(s, u; B_d, K^+, \pi^-) &= \sum_{i=3}^6 (a_i^c(K\pi) - a_i^u(K\pi)) \langle Q_i \rangle_{\text{fact}} + \tilde{P}_1^{\text{GIM}}, \end{aligned} \quad (3)$$

where  $\langle Q_i \rangle_{\text{fact}}$  denotes the factorized matrix element, and the parameters  $a_i$  are defined in [9]. The tilded parameters represent  $\Lambda_{QCD}/m_b$  corrections; in  $B \rightarrow K\pi$  channels the only Cabibbo-enhanced correction is given by  $\tilde{P}_1$ . This term has no arguments since we take it in the  $SU(3)$  symmetry limit.

We use input parameters (like  $\bar{\rho}$ ,  $\bar{\eta}$ , the form factors) with errors, and extract output quantities (like the  $BR$ s, the asymmetries, but also  $\gamma$ , or the form factors when they are not used as inputs) with their uncertainties. Let us explain how we used the input errors and extracted the output uncertainties. We proceed with the usual likelihood method, by generating the input quantities weighted by their probability density function (p.d.f.). In the case of theoretical quantities this is assumed to be flat, whereas the experimental quantities are extracted with Gaussian

distributions. Probability density functions, averages and standard deviations are then obtained by weighting the output quantities by the likelihood factor

$$\mathcal{L} = e^{-\frac{1}{2} \sum_i (BR_i - BR_i^{exp})^2 / \sigma_i^2}, \quad (4)$$

where  $\sigma_i$  are the standard deviations of the experimental  $BR$ s,  $BR_i^{exp}$ , given in table 1. In cases where the experimental input has a systematic error dominated by theoretical uncertainties, we should extract the latter with a flat distribution [18]. We have instead combined the errors in quadrature and extracted all the experimental quantities with gaussian distributions. Within the present accuracy, and taking into account the unknown non-perturbative parameters, this procedure is fully justified. We have also verified that by extracting the theoretical errors with a gaussian distribution, we obtain very similar results. For more details on the likelihood procedure, the reader is referred to [18], where all aspects are discussed at length.

## Results with factorization

We start by considering the case in which we use factorization and take the CKM parameters  $|V_{ub}|$  and  $\gamma$  from other experimental determinations. We discuss first  $BR(B^+ \rightarrow \pi^+\pi^0)$  since in this case, due to isospin symmetry, we do not have the complications due to penguin contractions. Thus, at fixed  $|V_{ub}|$ , the prediction for  $BR(B^+ \rightarrow \pi^+\pi^0)$  only depends on  $f_\pi(0)$  (trivial dependences as from  $f_\pi$  will be omitted in this discussion). By using the theoretical estimate and uncertainty of  $f_\pi(0)$  from [19], and taking into account the uncertainties on  $|V_{ub}|$ , we predict in this case  $BR(B^+ \rightarrow \pi^+\pi^0) = (5.0 \pm 1.5) \times 10^{-6}$  in very good agreement with the experimental average given in table 1. A complementary exercise is to use as input  $|V_{ub}|$  and the experimental value of  $BR(B^+ \rightarrow \pi^+\pi^0)$  in order to extract the value of  $f_\pi(0)$ . In this case we find  $f_\pi(0) = 0.28 \pm 0.06$ , in very good agreement with lattice and QCD sum rules estimates. This exercise shows that we do not need to rely on theoretical calculations for the form factors. Indeed also for  $f_K(0)$  we only need  $f_K(0)/f_\pi(0)$  which cannot differ too much from one. Moreover it is likely that a large part of the uncertainties of the theoretical predictions cancel in this ratio.

Here and in all the other cases where  $|V_{ub}|$  and  $\gamma$  are taken from other experimental determinations, we use as equivalent input parameters the values of  $\bar{\rho}$  and  $\bar{\eta}$  given in table 1 from the UTA analysis of ref. [18]. These values correspond to

$$\gamma = (54.8 \pm 6.2)^0. \quad (5)$$

By using  $f_\pi(0)$  either from theory or from the fit to  $BR(B^+ \rightarrow \pi^+\pi^0)$  and assuming factorization, we then predict  $BR(B_d \rightarrow \pi^+\pi^-)$  as a function of  $\gamma$  only. Besides, in order to analyze all  $B \rightarrow K\pi$  decays, we only need  $f_K(0)/f_\pi(0)$  to which the previous considerations apply. Alternatively we may take only  $|V_{ub}|$  from the experiments and fit the value of  $\gamma$ . In the first case, the results are given in table 2 labeled as “ $\gamma$  UTA” and show a generalized disagreement between predictions and experimental data. In the second case, the value of  $\gamma$  is fitted and

$f_\pi(0)$	$0.27 \pm 0.08$	$f_K(0)/f_\pi(0)$	$1.2 \pm 0.1$
$\rho$	$0.224 \pm 0.038$	$\eta$	$0.317 \pm 0.040$
$BR(B_d \rightarrow K^0 \pi^0)$	$10.4 \pm 2.6$	$BR(B^+ \rightarrow K^+ \pi^0)$	$12.1 \pm 1.7$
$BR(B^+ \rightarrow K^0 \pi^+)$	$17.2 \pm 2.6$	$BR(B_d \rightarrow K^+ \pi^-)$	$17.2 \pm 1.6$
$BR(B_d \rightarrow \pi^+ \pi^-)$	$4.4 \pm 0.9$	$BR(B^+ \rightarrow \pi^+ \pi^0)$	$5.2 \pm 1.7$

Table 1: *Input values used in the numerical analysis. The form factors are taken from refs. [19, 20], the CKM parameters from ref. [18] and the BRs correspond to our average of CLEO, BaBar and Belle results [15, 16, 17]. All the BRs are given in units of  $10^{-6}$ .*

$BR$	$\gamma$ UTA	$\gamma$ free	$BR$	$\gamma$ UTA	$\gamma$ free
$K^0 \pi^0$	$5.9 \pm 0.2$	$5.7 \pm 0.4$	$K^+ \pi^0$	$4.8 \pm 0.2$	$9.1 \pm 0.5$
$K^0 \pi^+$	$11.7 \pm 0.5$	$11.6 \pm 0.8$	$K^+ \pi^-$	$9.8 \pm 0.4$	$17.7 \pm 1.0$
$\pi^+ \pi^-$	$8.5 \pm 0.3$	$5.1 \pm 0.7$	$\pi^+ \pi^0$	$4.2 \pm 0.2$	$5.4 \pm 0.6$
$\pi^0 \pi^0$	$0.19 \pm 0.01$	$0.59 \pm 0.04$			

Table 2: *Results for the BRs obtained with factorization without charming or GIM penguins. All the BRs are given in units of  $10^{-6}$ .*

the results are labeled as “ $\gamma$  free”. In this case the disagreement is reduced for  $BR(B^+ \rightarrow K^+ \pi^0)$  and  $BR(B_d \rightarrow K^+ \pi^-)$ , and also for  $BR(B_d \rightarrow \pi^+ \pi^-)$ , but it remains sizable for  $BR(B_d \rightarrow K^0 \pi^0)$  and  $BR(B^+ \rightarrow K^0 \pi^+)$ . The pattern  $BR(B^+ \rightarrow K^0 \pi^+):BR(B_d \rightarrow K^+ \pi^-):BR(B_d \rightarrow K^0 \pi^0):BR(B^+ \rightarrow K^+ \pi^0)=2:2:1:1$ , which is suggested by the data, and is well reproduced when the contribution of the charming penguins is large, as discussed in the following, is lost in this case. Moreover the fitted value of  $\gamma = (163 \pm 12)^0$  is in striking disagreement with the results of the UTA. Although one may question on the quoted uncertainty of the UTA result, it is clearly impossible to reconcile the two numbers. Thus either there is new physics or  $\Lambda_{QCD}/m_b$  corrections are important. We now discuss the latter possibility.

### Factorization with Charming and GIM penguins

We now discuss the effects of charming penguins, parameterized by  $\tilde{P}_1$ .  $\tilde{P}_1$  is a complex amplitude that we fit on the  $B \rightarrow K\pi$  BRs. In order to have a reference scale for its size, we introduce a suitable “Bag” parameter,  $\tilde{B}_1$ , by writing

$$\tilde{P}_1 = \frac{G_F}{\sqrt{2}} f_\pi f_\pi(0) g_1 \tilde{B}_1, \quad (6)$$

where  $G_F$  is the Fermi constant. We use  $f_\pi(0)$  for both  $B \rightarrow K\pi$  and  $B \rightarrow \pi\pi$  channels since, as mentioned before, for charming penguins we work in the  $SU(3)$  limit.  $g_1$  is a Clebsch-Gordan parameter depending on the final  $K\pi$  ( $\pi\pi$ ) channel.

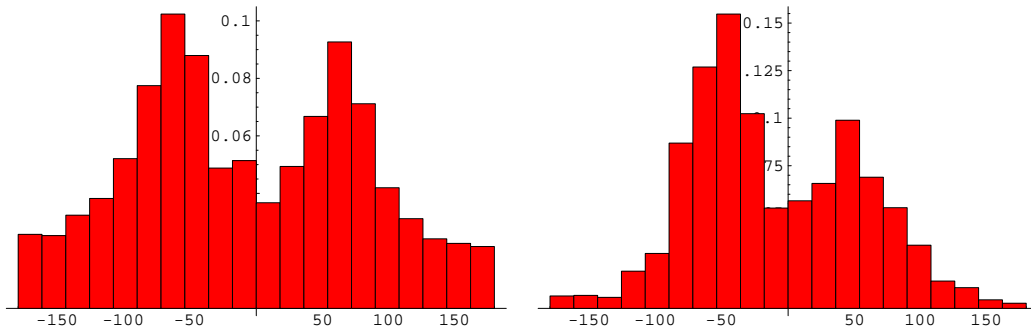


Figure 1: *p.d.f. for  $\phi$ , in the case where only  $\tilde{P}_1$  (left) and both  $\tilde{P}_1$  and  $\tilde{P}_1^{\text{GIM}}$  (right) are included.*

In the case where  $|V_{ub}|$  and  $\gamma$  are taken from the UTA, by fitting the  $B \rightarrow K\pi$  channels and  $B^+ \rightarrow \pi^+\pi^0$  only, we find

$$|\tilde{B}_1| = 0.14 \pm 0.05. \quad (7)$$

Note that the size of the charming penguin effects is of the expected magnitude. As for the phase  $\phi = \text{Arg}(\tilde{B}_1)$ , it is very instructive to consider its distribution, which is displayed in fig. 1: the preferred value of  $\phi$  has a sign ambiguity since we are fitting the average of the  $B_d^0$  and  $\bar{B}_d^0$  BRs (or of the  $B^+$  and  $B^-$  BRs). The ambiguity can be resolved by measuring separately particle and anti-particle BRs. By using the distribution on the left of fig. 1, we compute the mean value of  $|\phi|$  with the result  $|\phi| = (75 \pm 44)^\circ$  and leave the sign undetermined. This is a reasonable procedure, given the approximate symmetry of the distribution and the large uncertainty. In view of the discussion of the particle-antiparticle asymmetry which we present at the end of this paper, we note here that the value of  $\phi$  could be rather large. In table 3 we give the corresponding predicted values and uncertainties for the relevant branching ratios (label “Charming”). We observe a remarkable improvement for the  $K\pi$  channels and a large shift in the value of  $BR(B_d \rightarrow \pi^0\pi^0)$ <sup>2</sup>, in spite of the fact that in the latter case penguin effects are not Cabibbo enhanced (the  $\pi^0\pi^0$  amplitude is however colour suppressed). The predicted value for  $BR(B_d \rightarrow \pi^+\pi^-)$  remains however much larger than the experimental one.

If one fits the  $B \rightarrow K\pi$  channels,  $B^+ \rightarrow \pi^+\pi^0$  and  $B_d \rightarrow \pi^+\pi^-$  simultaneously, one finds a better agreement for  $BR(B_d \rightarrow \pi^+\pi^-)$  but a rather small value for  $BR(B^+ \rightarrow \pi^+\pi^0)$  (column “Charming with  $\pi^+\pi^-$ ” of table 3). This happens at the price of reducing the fitted value of the form factor,  $f_\pi(0) \sim 0.22$ , which is pushed down by  $BR(B_d \rightarrow \pi^+\pi^-)$ . In fact the latter has an experimental error much smaller than  $BR(B^+ \rightarrow \pi^+\pi^0)$ , and therefore governs the fit. However, we do not think that this is the correct procedure: theoretically,  $BR(B^+ \rightarrow \pi^+\pi^0)$  is on much more solid grounds than  $BR(B_d \rightarrow \pi^+\pi^-)$ , since it is not affected by penguins or annihilations, and thus is much more suitable to constrain  $f_\pi(0)$ .

<sup>2</sup>This effect was already noticed in [11].



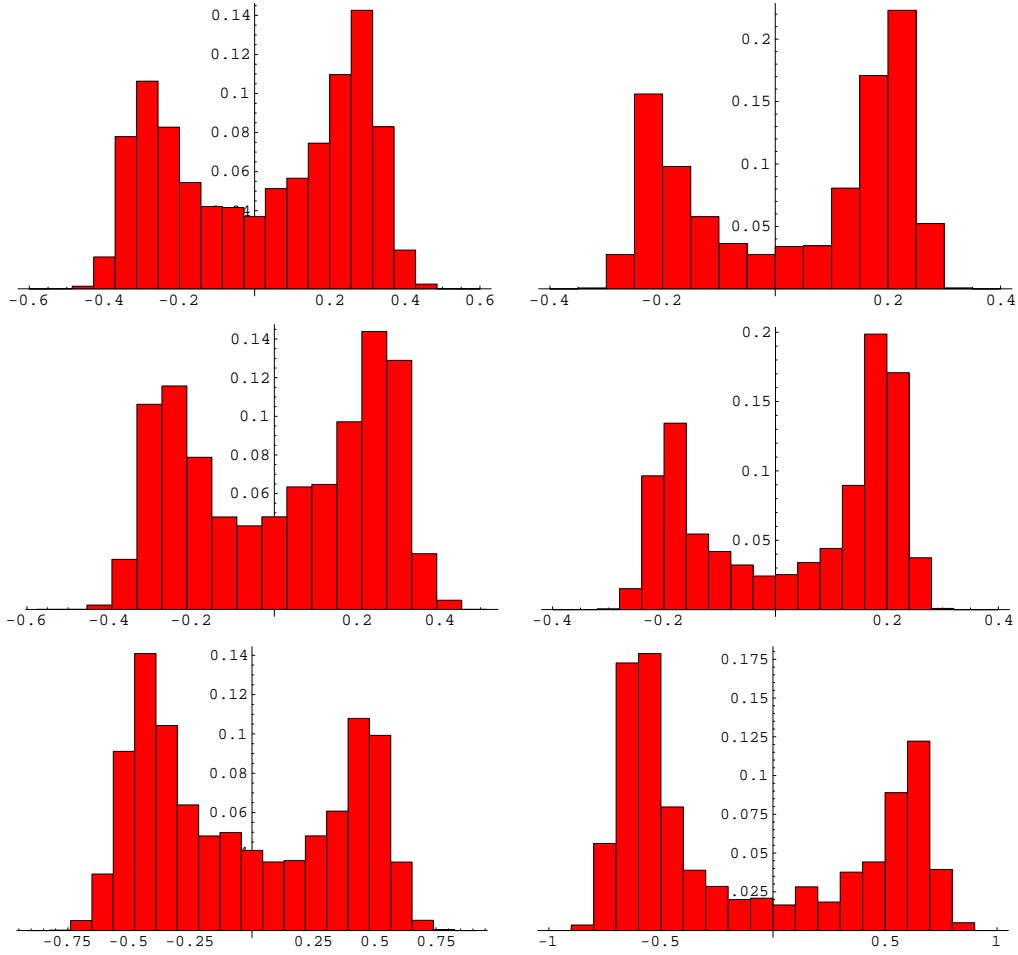


Figure 2: *p.d.f.* for the largest *CP* asymmetries, in the case where only  $\tilde{P}_1$  (left) and both  $\tilde{P}_1$  and  $P_1^{\text{GIM}}$  (right) are included. From top to bottom, we give  $\mathcal{A}(B^+ \rightarrow K^+\pi^0)$ ,  $\mathcal{A}(B_d \rightarrow K^+\pi^-)$  and  $\mathcal{A}(B_d \rightarrow \pi^+\pi^-)$ .

$BR$	Charming	Charming with $\pi^+\pi^-$	Charming + GIM	$BR$	Charming	Charming with $\pi^+\pi^-$	Charming + GIM
$K^0\pi^0$	$9.2 \pm 1.1$	$8.7 \pm 0.9$	$8.8 \pm 1.0$	$K^+\pi^0$	$9.2 \pm 0.8$	$9.3 \pm 0.7$	$9.3 \pm 0.7$
$K^0\pi^+$	$18.3 \pm 2.1$	$17.4 \pm 1.8$	$17.6 \pm 1.8$	$K^+\pi^-$	$18.2 \pm 1.4$	$18.6 \pm 1.4$	$18.4 \pm 1.3$
$\pi^+\pi^-$	$9.1 \pm 2.5$	$5.1 \pm 1.8$	$4.7 \pm 0.8$	$\pi^+\pi^0$	$4.8 \pm 1.4$	$2.7 \pm 0.5$	$3.5 \pm 0.9$
$\pi^0\pi^0$	$0.37 \pm 0.05$	$0.36 \pm 0.05$	$0.69 \pm 0.30$				

Table 3: *BRs* with charming or charming and GIM penguins. All the *BRs* are given in units of  $10^{-6}$ .

In order to reduce the predicted  $BR(B_d \rightarrow \pi^+\pi^-)$  without affecting  $BR(B^+ \rightarrow \pi^+\pi^0)$ , one may include other effects of the same order of the charming penguins, as for example the GIM penguins introduced in ref. [11]. In this case we fit all the  $BR$ s given in table 1. With GIM and charming penguins included, we find

$$\begin{aligned} |\tilde{B}_1| &= 0.16 \pm 0.03, & |\phi| &= (56 \pm 32)^{\circ}, \\ |\tilde{B}_1^{\text{GIM}}| &= 0.23 \pm 0.11, & |\phi^{\text{GIM}}| &= (135 \pm 37)^{\circ}, \end{aligned} \quad (8)$$

where the notation is self-explaining. We have given the absolute value of  $\phi$  since, as in the previous case, the sign ambiguity persists when we include GIM penguins. The distribution is also shown in fig. 1. The results for the  $BR$ s can be found in table 3 with the label “Charming+GIM”. They show that the extra GIM parameter improves the agreement for the measured  $B \rightarrow \pi\pi$   $BR$ s. We do not claim, however, to be able to predict  $BR(B_d \rightarrow \pi^+\pi^-)$ : our results instead show that accurate predictions for  $B_d \rightarrow \pi\pi$  decays can only be obtained by controlling quantitatively the  $\mathcal{O}(\Lambda_{QCD}/m_b)$  corrections, which is presently beyond the theoretical reach. Estimates for charming penguin effects can also be obtained by using some phenomenological model, as for example done in ref. [12]. We observe that the sensitivity of the  $BR$ s to the value of  $\gamma$  is lost, with the present experimental accuracy, once penguin effects are introduced. Indeed when one tries to fit  $B_1$  ( $B_1^{\text{GIM}}$ ) and  $\gamma$  simultaneously, one finds that the value of  $\gamma$  is essentially undetermined. From the above discussion it clearly emerges that one of the important step for the improvement of this kind of analyses is a more precise measurement of  $BR(B^+ \rightarrow \pi^+\pi^0)$ .

## Particle–Antiparticle asymmetries for the Branching Ratios

The large absolute values of  $\phi$ , and the sizable effects that penguins have on the  $BR$ s, stimulated us to consider whether we could find observable particle-antiparticle asymmetries as the one defined in eq. (1). We find large effects in  $BR(B^+ \rightarrow K^+\pi^0)$ ,  $BR(B_d \rightarrow K^+\pi^-)$  and  $BR(B_d \rightarrow \pi^+\pi^-)$ , as shown in fig. 2. As discussed before, for  $BR(B_d \rightarrow \pi^+\pi^-)$  our predictions suffer from very large uncertainties due to contributions which cannot be fixed theoretically. For this reason, the values of the asymmetry reported in table 4 are only an indication that a large asymmetry could be observed also in this channel. The sign ambiguity of  $\phi$  is reflected in the asymmetry  $\mathcal{A} \sim \sin \gamma \sin \phi$ . This ambiguity can be solved only by an experimental measurement or, but this is extremely remote, by a theoretical calculation of the relevant amplitudes. For each channel, we give the absolute value of the asymmetry in table 4. Note that within factorization all asymmetries would be unobservably small, since the strong phase is a perturbative effect of  $\mathcal{O}(\alpha_s)$  [9]. The possibility of observing large asymmetries in these decays opens new perspectives. These points will be the subject of a future study.

$ \mathcal{A} $	Charming	Charming + GIM	$ \mathcal{A} $	Charming	Charming + GIM
$K^0\pi^0$	$0.02 \pm 0.01$	$0.05 \pm 0.03$	$K^+\pi^0$	$0.23 \pm 0.10$	$0.18 \pm 0.06$
$K^0\pi^+$	$0.00 \pm 0.00$	$0.03 \pm 0.03$	$K^+\pi^-$	$0.21 \pm 0.10$	$0.17 \pm 0.06$
$\pi^+\pi^-$	$0.36 \pm 0.16$	$0.52 \pm 0.18$	$\pi^0\pi^0$	$0.40 \pm 0.19$	$0.58 \pm 0.29$

Table 4: *Absolute values of the rate CP asymmetries for  $B \rightarrow K\pi$  and  $B \rightarrow \pi\pi$  decays. The columns labeled by “Charming” and “Charming + GIM” correspond respectively to the cases in which only  $\tilde{P}_1$  and both  $\tilde{P}_1$  and  $\tilde{P}_1^{\text{GIM}}$  are introduced. The asymmetry in  $B \rightarrow \pi^+\pi^0$  vanishes exactly.*

## Conclusion

We have analyzed the predictions of factorization for  $B \rightarrow \pi\pi$  and  $B \rightarrow K\pi$  decays. We note that the normalization of all the other  $BR$ s is essentially fixed by the value of  $BR(B^+ \rightarrow \pi^+\pi^0)$  and  $SU(3)$  symmetry. Even taking into account the uncertainties of the input parameters, we find that factorization is unable to reproduce the observed  $BR$ s. The introduction of charming and GIM penguins [11] allows to reconcile the theoretical predictions with the data. It also shows however that it is not possible, with the present theoretical and experimental accuracy, to determine the CP violation angle  $\gamma$ . Contrary to factorization, we predict large asymmetries for several of the particle–antiparticle  $BR$ s, in particular  $BR(B^+ \rightarrow K^+\pi^0)$ ,  $BR(B_d \rightarrow K^+\pi^-)$  and  $BR(B_d \rightarrow \pi^+\pi^-)$ . This opens new perspectives for the study of CP violation in  $B$  systems.

## Acknowledgments

We thank G. Buchalla and C. Sachrajda for useful discussions on our work. M.C. thanks the TH division at CERN where part of this work has been done. L.S. thanks Hsiang-nan Li for very informative discussions and J. Matias for pointing out a misprint.

## References

- [1] M. Ciuchini, E. Franco, G. Martinelli, A. Masiero and L. Silvestrini, Phys. Rev. Lett. **79** (1997) 978, [hep-ph/9704274](#).
- [2] R. Barbieri and A. Strumia, Nucl. Phys. B **508** (1997) 3, [hep-ph/9704402](#).
- [3] R. Fleischer and T. Mannel, [hep-ph/9706261](#).
- [4] A. F. Falk, A. L. Kagan, Y. Nir and A. A. Petrov, Phys. Rev. D **57** (1998) 4290, [hep-ph/9712225](#).
- [5] S. Baek and P. Ko, Phys. Rev. Lett. **83** (1999) 488, [hep-ph/9812229](#).

- [6] *The Babar Physics Book*, edited by P.F. Harrison and H.R. Quinn, SLAC report SLAC-R-504, October 1998.
- [7] F. Takasaki, in *Proc. of the 19th Intl. Symp. on Photon and Lepton Interactions at High Energy LP99* ed. J.A. Jaros and M.E. Peskin, Int. J. Mod. Phys. A **15S1** (2000) 12, [hep-ex/9912004](#).
- [8] H-n Li and H.L. Yu, Phys. Rev. Lett. **74** (1995) 4388 and Phys. Rev. D **53** (1996) 2480; C.H. Chang and H-n Li, Phys. Rev. D **55** (1997) 5577; T.W. Yeh and H-n Li, Phys. Rev. D **56** (1997) 1615; H.Y. Cheng, H-n Li and K.C. Yang, Phys. Rev. D **60** (1999) 094005; for a recent review see H-n Li, [hep-ph/0103305](#).
- [9] M. Beneke, G. Buchalla, M. Neubert and C.T. Sachrajda, Phys. Rev. Lett. **83** (1999) 1914; Nucl. Phys. B **591** (2000) 313; [hep-ph/0007256](#).
- [10] J.D. Bjorken, Nucl. Phys. B (Proc. Suppl.) **11** (1989) 325; M. J. Dugan and B. Grinstein, Phys. Lett. B **255** (1991) 583; H. D. Politzer and M. B. Wise, Phys. Lett. B **257** (1991) 399.
- [11] M. Ciuchini, E. Franco, G. Martinelli and L. Silvestrini, Nucl. Phys. B **501** (1997) 271, [hep-ph/9703353](#). M. Ciuchini, R. Contino, E. Franco, G. Martinelli and L. Silvestrini, Nucl. Phys. B **512** (1998) 3, [hep-ph/9708222](#).
- [12] P. Colangelo, G. Nardulli, N. Paver and Riazuddin, Z. Phys. C **45** (1990) 575. C. Isola, M. Ladisa, G. Nardulli, T. N. Pham and P. Santorelli, [hep-ph/0101118](#).
- [13] A. J. Buras and R. Fleischer, Phys. Lett. B **341** (1995) 379, [hep-ph/9409244](#).
- [14] R. Godang *et al.* [CLEO Collaboration], Phys. Rev. Lett. **80** (1998) 3456, [hep-ex/9711010](#).
- [15] D. Cronin-Hennessy *et al.* [CLEO Collaboration], [hep-ex/0001010](#). D. M. Asner *et al.* [CLEO Collaboration], [hep-ex/0103040](#).
- [16] G. Cavoto, BaBar Collaboration, talk given at the XXXVI Rencontres de Moriond QCD.
- [17] B. Casey, Belle Collaboration, talk given at the XXXVI Rencontres de Moriond QCD.
- [18] M. Ciuchini *et al.*, [hep-ph/0012308](#).
- [19] A. Abada, D. Becirevic, P. Boucaud, J. P. Leroy, V. Lubicz and F. Meschia, [hep-lat/0011065](#). See also L. Del Debbio, J. M. Flynn, L. Lellouch and J. Nieves [UKQCD Collaboration], Phys. Lett. B **416** (1998) 392, [hep-lat/9708008](#).
- [20] A. Khodjamirian, R. Ruckl, S. Weinzierl, C. W. Winhart and O. Yakovlev, Phys. Rev. D **62** (2000) 114002, [hep-ph/0001297](#). For an earlier determination of the form factors, see also P. Ball, JHEP**9809** (1998) 005, [hep-ph/9802394](#).
- [21] LEP Working group on  $V_{ub}$ , <http://battagl.home.cern.ch/battagl/vub/vub.html>.
- [22] B.H. Behrens *et al.*, CLEO Collaboration, Phys. Rev. **D61** (2000) 052001.

- [23] A. J. Buras and L. Silvestrini, Nucl. Phys. B **569** (2000) 3, [hep-ph/9812392](#).
- [24] W. N. Cottingham, H. Mehrban and I. B. Whittingham, [hep-ph/0102012](#).
- [25] Y. Keum, H. Li and A. I. Sanda, [hep-ph/0004004](#); Y. Y. Keum, H. Li and A. I. Sanda, Phys. Rev. D **63** (2001) 054008, [hep-ph/0004173](#).
- [26] M. Beneke, [hep-ph/0009328](#).
- [27] A. Ali and C. Greub, Phys. Rev. D **57** (1998) 2996, [hep-ph/9707251](#);  
A. Ali, G. Kramer and C. Lu, Phys. Rev. D **58** (1998) 094009,  
[hep-ph/9804363](#); Phys. Rev. D **59** (1999) 014005, [hep-ph/9805403](#).